Design Science: Why, What and How

Panos Y. Papalambros

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Design Science
Editorial

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The *Design Science* journal is a designed product, maybe also a designed product-service system. After all the insights, experiences, data collections and scientific analyses have played their role, bringing a design into existence remains an act of faith. This journal is no exception. It is a collective act of faith by a large number of people who have put themselves forth as authors, readers, editors, reviewers, producers and sponsors. Why do we believe in this journal? What are its scope and purpose? How will we achieve them? We share our thoughts on these questions below.

We start with a discussion of the 'why' as it emerged from my own interactions with the community. Next we address the 'what' question. We asked our Editorial Board to offer an individual statement on the 'what' of design science: what they see as current and future design science research. We include their verbatim responses followed by John Gero's synthesis of the Board's ideas. Finally, we discuss the practicalities of how the journal hopes to support the 'what' vision in the years to come.

The connecting thread throughout the discussion here is the collective desire to build avenues of communication and understanding for an open, inclusive, boundary-crossing design community.

Why

Design as a recognized discipline is a relative newcomer in the research community. An established discipline involves both creation and dissemination of knowledge. In an academic setting, creation of knowledge is supported by research and dissemination of knowledge by education. Design research and education derive strong benefits from a more explicit use of the scientific method. Design is both art and science. Approaching design knowledge with the scientific method does not and should not negate art's presence in design; it is simply a matter of focus.

Design science studies the creation of artifacts and their embedding in our physical, psychological, economic, social and virtual environments. Good design improves our lives through innovative, sustainable products and services, creates value, and reduces or eliminates the negative unintended consequences of technology deployment. Bad design ruins our lives. In design science, product and system design is addressed by combining analysis and synthesis, and drawing from many scientific disciplines.

While this combination has become a discipline in its own right, the need to bring many diverse disciplines to bear on design is a critical element of good design and of good design science research. Thus, design *happens* in a diversity

Corresponding author
Panos Y. Papalambros
editor@descij.org

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of disciplines, each with its own language, culture and semantics. Exactly this diversity is the reason, the 'why,' the *Design Science* journal has been created: The journal aims to make all design research *accessible* to the widest possible audience; it aspires to be the meeting place for a design community that crosses the disciplinary boundaries and to offer entry points to those who wish to understand how other design researchers approach design questions in a rigorous manner. In doing so, it also aspires to strengthen all other design communities and to help them to thrive. This is one reason why several editors of other important design journals have agreed to serve on the *Design Science* Editorial Board and provide the requisite links.

In large part, my personal motivation to invest in this effort stems from my five-year experience as chief editor of the *Journal of Mechanical Design* (JMD), published by the American Society of Mechanical Engineers. I assumed my JMD editorial service at a pivotal moment that required a new synthesis of the journal's scope and constituencies. Even though I had always been partial to a design science approach (even before this term was adopted in its current meaning), over the time of my editorial duties I realized the confining boundaries of a discipline-specific design journal and the difficulty in reaching communities whose work we would actually use but with whom we had no venue to interact. While the discipline-specific depth is critical for scientific advances, the cross-discipline breadth is necessary for addressing the emerging larger challenges facing a technologically-based society. This realization is not unique to design. However, design is most often the instantiation of scientific knowledge put to use for society's benefit and as such carries a special burden to utilize this diversity of disciplinary knowledge.

My timing was right as the Design Society had also gradually reached the same conclusion and had been exploring ways to broaden its scope and become more inclusive. Moreover, given my engineering background it would be necessary to have a recognized non-engineering researcher join this effort. Again I was lucky to have known John Gero for many years and to secure his acceptance to jointly define and launch such a journal. Together we were fortunate to assemble a team of distinguished Editorial Board members who share their thoughts herein.

What

In what follows, I list our editors' take on the question of the present and future of design science research, which this journal is all about. There was no priming and no effort to harmonize opinions. I left the sense-making task to John Gero whose synthesis effort follows further below.

Saeema Ahmed–Kristensen

Design science has long tackled issues to support the practice of design engineering, including understanding the complexity of the products, understanding the people who design them and those who use them, the process of designing, together with the organization around the process. This understanding is built upon knowledge: from within the engineering domain, of modeling products, and human behavior in design; for example, understanding better the process of creativity, thus establishing the discipline of design research.

Although this research is not yet complete, products are becoming/have become more than physical products, including systems, digital technologies and services, changing the concepts of products, and the type of people and processes needed to design both the products and their user experience. There are many drivers of change in research for design science for the future: the increase in the development of new technology including the digital world, the use of social media connecting greater numbers of people, the availability of big data, products integrating with apps providing fast feedback, and transferring functionality from physical products to software.

With the new types of products that integrate digital components and/or services, the planned product development processes traditionally associated with the design of physical products are challenged. A greater level of agility is required in order to encompass a greater level of intensity of interaction between software, hardware and mechanical components together with services. A number of traditional manufacturing firms have already begun the transformation towards including more agile components into their product development processes. Designers within these agile processes work closer together in intense collaboration, co-developing ideas with team members from other disciplines, and require a greater understanding of multidisciplinary teams. The agile paradigm changes the current understanding of the evolution of the design of a product. The new generation of designers is required to possess knowledge of more than physical products and to understand the interaction between the physical and the non-tangible services, bringing the need to educate designers in a wider context.

The need to access large markets is increasing. Emerging markets require a greater understanding of the types of products that are needed, of cultures and the supporting infrastructures. The need to better understand the consumer and the user experience becomes apparent as both markets and types of products change.

The changing role of products, processes and people drives a need for design researchers to cross domains and bring insights from domains traditionally associated with engineering design but also from other fields. This opens the door for closer collaboration that benefits design research but also brings new knowledge of interest beyond design research.

Design science in the future is likely to be transdisciplinary, not only in borrowing research methods or theories from other fields and applying them to design problems as we do today, but also in impacting research beyond design to facilitate the new generation of products (systems/services/digital), processes and people.

Petra Badke-Schaub

'Prediction is very difficult, especially if it's about the future.' – *Niels Bohr* (brainyQuote.com). My reflections about the future of design research consist of three sections. In the first section, I will point out that human beings are not capable of making prognoses in a satisfying way; in the second part the main developments in design research are sketched, because prognoses have to be based on a description of the current situation; in the final section, thoughts about the future of design research will be pointed out.

The difficult task: forecasting the future of design research

When human beings make prognoses about the future, the cognitive process usually starts with the past, touches the present situation and adapts to the future to predict in a usually simple and linear way (trend extrapolation). A more sophisticated strategy may be to add an amount dependent on the distance into the future to be estimated. Both approaches can be successful as long as the prognosis is about short-term developments. Typical mid- and long-term predictions will deliver poor results. The main problems for that kind of prognosis are (a) linear extrapolations on a numeric scale, (b) conservative extrapolations on a structural scale and (c) the assumption that the future will follow the same influencing factors and behavior pattern as has been true in the past.

Many forecasts – even those by famous, knowledgeable people – are proven wrong in the future, both in terms of numbers but more crucially in terms of structural changes. This is true for laymen as well as for experts, which can be exemplified by the quote from IBM CEO Thomas Watson in the year 1943: 'I think there is a world market for maybe five computers.'

There is evidence then that human beings are not very well equipped to forecast for developments that are not characterized as continuous increase or decrease but are determined by apparently abrupt changes. One reason might be that human beings experience abrupt changes as continuous ones within a continuum.

The difficult past: historical development of design research

Having stated my concerns about the difficulty of viewing into the future, looking now into the past 50 years of design research, I see the development of such research in roughly five distinguishable phases.

1. The optimistic start: big questions – big names. In the early years when design research was starting to define the field of design and topics of research, the newly established design community shared a common goal that was mainly related to the complexity of design and the need to understand design and to support the design process.
2. This challenge was met by the development of complex design theories – covering mostly technical issues (see, for example, Hubka, V. & Eder, W.E. (1982) *Principles of Engineering Design*, Butterworth Scientific, London; Beitz, W., Wallace, K. & Pahl, G. (1984) *Engineering Design*, Design Council, London). New questions were asked, for example, taking the view from a meta-level of what design is and how design should be taught.

   Scientific considerations about common characteristics of design were brought up by well-recognized authors such as Herbert A. Simon (Simon, H.A. (1969, 1996) *The Sciences of the Artificial*, MIT Press, Cambridge, MA), Stuart Pugh (Pugh, S. (1991) *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley, Wokingham), Nigel Cross (Cross, N. (1989) *Engineering Design Methods*, Wiley, London) and Roozenburg and Eekels (Roozenburg, N.F.M. & Eekels, J. (1995) *Product Design: Fundamentals and Methods*, Wiley, London). Donald Schön (Schön, D.A. (1983) *The Reflective Practitioner: How Professionals Think in Action*, Basic, New York) in his design educational-oriented approach focused on how to teach new insights gained from the analysis of design.

3. Research challenge: theory differs. Theories were different from what was observed in thorough analysis of practicing designers' processes. From now on empirical research was the ubiquitous way to gain design knowledge, namely, empirical research in different laboratory and field settings, whether experiments or case studies. A multitude of methodological approaches were used but often in an individual adaption.
4. Disappointing insights: fragmentation instead of integration. Diving and drowning in complexity, a huge variety of empirical data were accumulated, often showing contradictory results and leaving the scientific community in a state of disappointment. Due to the panorama of scattered research results, it is not yet clear what the current knowledge shared by the design research community is.
5. Re-orientation in modesty: learning from others. There is a clear orientation in design research to make use of the research methodology of neighboring disciplines, and also from the theories of other disciplines, including human sciences. Most of these are carried out in different settings (field, laboratory, different disciplines, with different requirements and different groups of participants). As the theories were abolished, it became obvious that there is a lot of empirical research but a lack of explanations to integrate the multiple kinds of data in a coherent way.

The future of design research: three breaking developments

The following three issues will change design research in the upcoming years.

1. Increased easy access to 'brain data.' Brain data are big data. There are many questions about internal cognitive, motivational and emotional processes that influence thinking, reasoning and decision-making, which are yet unsolved. A better (easier, more reliable and more valid) access to the brain will open the collaboration between neuroscience and design research. This marriage can deliver new research questions, surprising results, new insights, and finally may provide new and better methods supporting the activity of designing and also the education in design.
2. New technology features new design processes. In the past 5–10 years we could observe the great change with regard to support of visualization in design. Three-dimensional printing and many other types of prototyping will change society with regard to many aspects. Service design can take a leading role in design.
3. New paradigms will support new approaches in design research while staying with the main goal, which is to understand and explain design processes. New and improved ways of communication allow a more collaborative research approach, which means a better exchange of information, knowledge and ideas.

As stated at the beginning, the future is difficult to foresee, especially in our complex and dynamic world, but what we know is that design research can help to make the designer work in ways that will make the world a little better.

Kristi Bauerly

It is important to respect and acknowledge the creativity and non-linear innovation inherent in the design process. It is so simple to accidentally destroy positive design ideas by turning on our analytical minds too early. The art of design is to keep multiple potential futures in mind at the same time, while the science of design is in predicting, analyzing and optimizing the tradeoffs of those potential futures. I am particularly interested in the abundant research opportunities that can help to quantify how humans fit in the designed world – or, perhaps more appropriately, ask how the designed world should accommodate a broad diversity of human needs, performance and behavior.

For example, does the design accommodate users of all ages? What is its impact on people from different cultures? How do ethnicity, education and gender impact a design? How do we design for varying capabilities in sight, hearing, taste, smell, touch, proprioception, pain, balance, vibration and temperature?

Is the design intuitive? Is it safe? Does it fit the human body? Is it comfortable? Is it perceptible? Does it integrate with other products and interfaces to optimize attention, concentration and effort? Can users effectively and efficiently interact with it and perform optimally?

Does the design fulfill a need? Does it improve the life of the user and humans in general? Is it attractive? Are users intrigued by it? Does it make people happy? Is it the appropriate salience? Is it reliable? Does it have an appropriate lifespan?

As the world becomes more designed, and as design touches more parts of our lives, these are the questions that should remain in the forefront of our minds.

Jean-Francois Boujut

Today there is a true interest in design research, and this field is often linked to innovation and the capacity to create new artifacts and shape the future of society through technological progress. It is not a bad thing to be in the limelight, but current vision is mostly too limited. As Simon wrote, 'design is the science of the artificial,' therefore the science of creating new things for the good of the humanity. It is therefore a global endeavor that spans from initial idea germination to engineering, production, service and disposal of products. Today most disciplines study design from a partial point of view, restricted to facets that do not reflect the whole picture. We have a pretty good knowledge of the managerial aspects of design, creativity methods or design cognition. Sociologists have studied groups of designers and engineers working on complex projects. We also have good results in automation or assistance of some repetitive and complicated tasks involving solution generation and evaluation. Information systems and decision-making are also part of the picture.

However, the parts put together do not reflect the whole picture. Recent theoretical approaches have attempted to offer unified theories of design. One of the main challenges is to build a unified theory of design while keeping the development of disciplinary approaches possible. Design is by essence trans-disciplinary. However, if design is recognized as a relevant research object by the respective scientific disciplines, then we can start to build really complementary approaches. We need a unified approach, not in terms of method and tools, but in terms of objective and aim.

We often see opposition to a so-called 'soft' approach versus a so-called 'hard' approach. This is childish! Design considered as a pure human activity reduced to social interactions is no more satisfactory than design considered as the production of artifacts reduced to physical laws. This is not to say that disciplinary approaches are useless; this is more a matter of unification of the approaches with methodological tools we can share. There is a clear need to agree on a corpus of methodologies that allow us to build a corpus of knowledge that can be shared, evaluated, discussed, and the results reproduced and double-checked. A cumulative approach is necessary if we want to be able to have scientific programs and build upon the works of others. The history and philosophy of science teaches us that the process is not purely cumulative; however, up to a certain extent it has to be.

If we want to build a future for design research, we have to build collectively rigorous approaches of the various phenomena we want to study using the available scientific approaches, theoretical or experimental, with the same rigor that allows the reproduction of the results and their falsification (in the sense of Karl Popper).

It is at this point that we can eventually claim that we have a scientific community.

Design research must be at the service of humanity to allow understanding of this marvelous phenomenon by which human beings are able to send some of their fellow men to walk on the Moon or to travel at the speed of sound across the oceans, but also to solve simple everyday problems.

Jonathan Cagan

Arguably the field of design science research began with Herb Simon's treatise (Simon, H.A. (1969) *op. cit.*). Since that time the field has blossomed into a rich understanding of how we design, why we design, and tools to help us design better. Those tools include human-based and computational-based ones. From the field of engineering, half of what engineers do is synthesis (a.k.a. design) while the other half is analysis. Yet, engineering education and the focus of many engineering researchers targets why things behave the way they do (analysis) and not how to make things behave the way we want them to (design). Understanding the synthesis process and how to aid it is the focus of design science.

The field of design science crosses discipline boundaries. The design part is based on the idea of big D versus little d. . . . There are many disciplines that design and that participate in the design process: engineers, industrial designers, architects, software creators, anthropologists, among others. The science part is the systematic study of the structure and behavior of the world. On one hand, the world in this case is synthetic in that it is the world created by people. On the other, the world is natural in that we study how people design. This latter aspect requires participants with knowledge of the social sciences such as cognitive and social psychology, anthropology, and others.

As we look to the future, design science must better inform the way that people search a dynamic design space, overcome fixation and reach creative potential (e.g. Tseng, I., Moss, J., Cagan, J. & Kotovsky, K. (2008) 'The role of timing and analogical similarity in the stimulation of idea generation in design,' *Design Studies*, Vol 29, pp. 203–221 and McComb, C., Cagan, J. & Kotovsky, K. (2015) 'Rolling with the punches: an examination of team performance in a design task subject to drastic changes,' *Design Studies*, Vol. 36, January, pp. 99–121). We need to understand how engineers are able to reason through complex situations to create multi-scale systems that solve hard problems (e.g. Egan, P., Cagan, J., Schunn, C. & LeDuc, P. (2015) 'Synergistic human-agent methods for deriving effective search strategies: the case of nanoscale design,' *Research in Engineering Design*, DOI: 10.1007/s00163-015-0190-3, 2015). We need to use this understanding to be able to improve the effectiveness and efficiency of design both by humans and by computers. On the computational side, search must be informed by cognitive models and mechanisms while leveraging numerical search (e.g., Fu, K., Cagan, J., Kotovsky, K. & Wood, K.L. (2013) 'Discovering structure in design databases through functional and surface based mapping,' *ASME Journal of Mechanical Design*, 135(3), 031006). A new frontier, mapping how the brain negotiates design solutions, will result in a deeper understanding of what aspects of reasoning are most critical to making design decisions and consumer choice, and associating those decisions with other decisions that people make (e.g., Sylcott, B., Cagan, J. & Tabibnia, G. (2013) 'Understanding consumer tradeoffs between form and function through meta-conjoint and cognitive neuroscience analyses,' *ASME Journal of Mechanical Design*, 135(10), 101002).

The synergistic relationship between human and computer search will enable an iterative approach that is guided by human intuition and optimized by rapid computational exploration. Humans can inform computer strategy and computers can refine those strategies, returning more effective strategies to people (e.g., Egan, et al. (2015) *op. cit.* and McComb et al. (2015) *op. cit.*).

To accomplish these challenges, an interdisciplinary approach is needed which leverages engineering design, psychology and analytical disciplines, among others. The result will be a holistic understanding of how people do and should design solutions to the world's most challenging problems.

Marco Cantamessa

Similarly to management science, design science emerges out of the seemingly incoherent juxtaposition of a professional activity and the scientific approaches used to study and support it (Simon, H.A. (1969) *op. cit.*; Cross, N. (2001) 'Designerly ways of knowing: design discipline versus design science,' *Design Issues*, 17(3), 49–55). If we want to have a glimpse into the future of design science, we must therefore try to foresee which trends will characterize both of its constituent elements, i.e., design and science.

Concerning *design*, over recent years we have witnessed a significant broadening of the areas to which design activity can be applied. Design is no longer limited to artifacts such as manufactured products, machinery or buildings. Moreover, thanks to the popularization of *design thinking* (Rowe, G.P. (1987, 1991) *Design Thinking*, MIT Press, Cambridge, MA), design is nowadays viewed as an essential tool for creatively solving wicked problems in business and society, as well as a key competence for modern managers (Martin, R.L. (2007) *The Opposable Mind: How Successful Leaders Win through Integrative Thinking*, Harvard Business School, Boston, MA). This trend is bound to continue, especially if researchers in the design science community will abandon their comfort zones and pick up the opportunity of directing their attention to emerging fields in the economy and in society, and to which design can successfully be applied. Examples are services, business models, and policy-making (Cantamessa, M. (2011) 'Design. . .but of what?' in H. Birkhofer (ed.), *The Future of Design Methodology*, Springer-Verlag, London).

Concerning *science*, we are slowly observing an increase in the methodological rigor with which design is being studied, in either experimental, empirical or normative work. This consolidation of the research paradigm is emerging because researchers in the community are becoming more and more inclined to build on others' results. Moreover, they are also becoming more proficient in the use of scientifically grounded methods coming from a number of relevant disciplines. Among the scientific approaches that will probably cast a significant influence on design research over the next few years, I see great promise in cognitive neuroscience and in the use of big data. The former will allow a very deep understanding of how designers act (for instance, see Sawyer, K. (2011) 'The cognitive neuroscience of creativity: a critical review,' *Creativity Research Journal*, 23(2), 137–154). The latter will allow the analysis of design processes occurring in the field with little effort, at the same time minimizing the intrusiveness of the research activity on the process itself.

Amaresh Chakrabarti

Discussion of design science requires a definition of design that is generic enough to encompass its research community. Here, the definition by Simon (Simon, H.A. (1969) *op. cit.*) is adapted: design is a purposeful activity aimed at changing existing situations into preferred ones. The word design has two meanings: as verb and as noun. The verb describes the act of designing; the noun specifies its outcomes. A *design* is taken here as a *plan* for intervention which, when implemented, is *intended* to change an undesirable situation into a (less un-) desirable one. *Designing* is the process of identifying these situations, as well as of developing designs to support the transition. This definition encapsulates several essential, generic features of design.

- Designs are *plans for intervention* that may include artefacts. Not all designs include artefacts, and not all designs consist of artefacts only.
- The concepts of *undesirable and desirable situations* are essential to the act of designing. Without an undesirable situation, there is no designing.
- Designing involves identifying these situations *as well as* developing the plan with which to change the undesirable into desirable.
- It is the *implementation* of the design, and not the design itself, that actualizes change.
- A design is implemented with the hope that it will bring in the desired change, which *may or may not happen*; hence the need for design science.

Design science involves developing design knowledge – both 'knowledge of design and knowledge for design' (Horvath, I. (2001) 'A contemporary survey of scientific research into engineering design,' in S. Culley et al. (eds) (2001) *International Conference on Engineering Design*, IMechE, Glasgow, pp. 13–20) – i.e., *descriptive knowledge* providing understanding of phenomena associated with design, and, based on this, *prescriptive knowledge*, i.e., support in the form of approaches, guidelines, methods or tools, for improving design practice and education (Blessing, L.T. & Chakrabarti, A. (2009) *DRM, a Design Research Methodology*, Springer, London). What are these phenomena associated with design? In Blessing et al., several facets are mentioned that are inherent to these phenomena: people, products, processes, knowledge and tools, organization, micro-economy and macro-economy. Phenomena associated with design – henceforth called *design phenomena* – are taken here as those that *govern the relationships between design and its facets* (Chakrabarti, A. (2011) 'Towards a taxonomy of design research areas', in H. Birkhofer (ed.) *The Future of Design Methodology*, Springer, London, pp. 249–259).

To understand the nature of design science, we contrast it with similar disciplines. Medicine as a discipline is similar to design science: it also develops descriptive theories/models of how organisms and their health work, and prescriptive support for improving (or destroying) the health of these organisms. Economics develops descriptive theories/models of how an economy works, and prescriptive support to change or maintain the economy in the preferred manner.

While design science is similar to these in that it too has both descriptive and prescriptive goals, it is distinctive in that unlike in these disciplines, the focus in design science is on design phenomena. Design science is, therefore, defined here as follows: *it is the science that develops knowledge of the relationships between design and its facets so as to better support design*. For instance, creativity *per se* may not be an area of design science, and may belong to psychology (individual creativity) or sociology (social creativity). However, design creativity is indeed an area of design science, as it explores the nature, roles and influences of creativity in/on designing.

Many researchers opine that despite design science being around for over half a century, it is unclear how well the discipline has academically matured. Three major issues are highlighted: a lack of overview of existing research, a lack of scientific rigour and a lack of use of results in practice. DRM (Blessing et al. 2009, *op. cit.*) has been developed with the intent of supporting design science to become more rigorous, and to offer a framework for comparing apparently disparate pieces of research in a coherent fashion using seven design research types. The resulting greater rigour and clearer usage context, it is hoped, would make it easier for results from design science to be defended with regard to their potential impact on practice, leading to smoother transition to practice. However, despite these and several attempts at developing ontologies of design and design knowledge, results from design science still seem hard to relate to one another.

Several researchers (e.g. Birkhofer, H. (2006) 'The consolidation of design science – a critical review of the status and some proposals to improve it', *2006 Applied Engineering Design Science Workshop*, S. Hosnedl and V. Vanek (eds), Pilsen, Czech Republic, pp. 13–22) propose consolidation, the integration of the various pieces of knowledge developed in design science. This is important for greater clarity on both how the various outcomes of design science relate to one another and on what the major milestones achieved have been, so that progress can happen more systematically, using earlier work as a foundation for developing new knowledge.

Future research in design science should pursue the following three types of consolidation.

- Consolidation of design phenomena: there is need for greater clarity as to what the various design phenomena are; consolidation should list these out.

- Consolidation of research areas in design science: lack of consolidation of this type is evidenced by the large variety and overlap of topics in conferences in design science.
- Consolidation of terms and concepts to describe design science: lack of consolidation of this type is indicated by the significant variation in meaning in even the most commonly used terms, e.g., function, as used across various pieces of research. Similar terms are used to mean different concepts, and similar concepts are expressed using different terms.

If carried out properly, consolidation should support progress in design science in multiple ways.

- Internal growth: consolidation should lead to less duplication of work, more efficient communication among researchers and more systematic and efficient development of design science based on relevant, previous research.
- External recognition: there would be a clear, easily recognizable body of knowledge in design science, with major milestones with greater scientific rigour and wider applications in practice.

Consolidation, however, cannot be dictated top-down; it must develop bottom-up, somewhat like the way in which standards develop in emergent areas with voluntary contribution from multiple stakeholders. What we need is a platform for research groups to voluntarily come together to collectively work on consolidation. Drawing on from the three types of consolidation proposed earlier in this editorial, four major consolidation tasks are proposed.

- Develop a preliminary taxonomy of phenomena related to design.
- Develop a preliminary taxonomy of areas in design science.
- Develop a repository of design research papers and classify these using the above taxonomies.
- Develop a lexicon of terms and concepts used in the research papers within each research area.

These can be used as starting points to encourage further research groups to join and work together, contributing to the development of a more coherent view of the overall discipline of design science, charting out its progress as well as its major, outstanding research challenges.

Lin-Lin Chen

In *The Structure of Scientific Revolutions*, Kuhn summarized how a discipline is formed in five stages, with the 'formation of specialized journals' as the first stage, followed by the 'foundation of professional societies,' the 'claim to a special place in academe,' the establishment of a common foundation of knowledge, and, finally, the proliferation of scholarly articles that build upon this shared foundation of knowledge.

Against these five development stages, it is clear that design, while increasingly being recognized as a discipline in its own right, still has a long way to go. Even after years of efforts by many design researchers, the number of journals – in which knowledge in design can be proposed, debated, verified, conserved and transformed – remains very limited. To reach the final goal of building a common foundation of knowledge in design, we need more high-quality journals that aim to publish rigorous design research. Therefore, as a design researcher and the Editor of *International Journal of Design*, I am extremely happy to support and contribute to *Design Science*.

In my view, the launch of *Design Science* is significant in several aspects. By focusing on science as a means to generate archival design knowledge, the journal explicitly welcomes both quantitative and qualitative research, thus broadening its scope beyond the engineering-focused design journals. As a designer who is naturally attracted to beautifully designed artifacts and systems, I am glad that *Design Science* does not shy away from discussing the less abstract and not always quantifiable world of designed objects and systems. When design is moving away from products to systems and services, it is great to see that *Design Science* acknowledges the fact that we can no longer deal with stand-alone products in laboratories, but must discuss their embedding in the physical, virtual, psychological, economic and social environment. Finally, as I have argued in an editorial (Chen, L.-L. (2007) 'International Journal of Design: a step forward,' *International Journal of Design*, 1(1), 1–2), the discipline of design will benefit from having more high-quality design research published in open-access journals, freely available to anyone, anywhere. The launch of *Design Science* is an important step for design towards a fully recognized discipline.

To design researchers all over the world, I want to say that we have a choice: we can choose to submit our best research works to well-established journals in another discipline, in which case we shall never have first-rate design journals, or we can choose to contribute our best works to a promising journal in design, and together we build our common foundation of knowledge in design. I have made my choice; it is now yours.

Wei Chen

Design involves people, processes, artifacts and systems. The underlying principle that distinguishes design research from other discipline areas is the inherent need for multidisciplinary knowledge and exploration that crosses boundaries of multiple disciplines involved in design, such as engineering, social science, arts and architecture, economics, business and management, computer and information science, communication studies, etc. Real design problems are not defined solely by technical concerns. They involve humans, groups, organizations and societies, and they impact law and business, raising new issues related to ethical and environmental concerns that call for cross-disciplinary collaborations and research.

One main theme in design science is the need for exploring the intersection and interaction of people, products (including services) and systems. By people, we mean both users and designers. Design science research calls for a deep understanding of the basic principles of design as a process of value creation, and from the education research point of view, a framework of learning. Successful design science research should disclose and address the challenging interdisciplinary issues in design, and provide a framework for integrating principles, methods (both qualitative and quantitative), and tools developed from multiple fields. For example, fundamental techniques in social science research can be combined with process and system design methods in engineering to better design complex systems such as health care and finance.

Whereas research in marketing explores what actions can attract people to purchase products, research in design explores how we can change our design process to include consumer needs to produce more attractive designs. Significant research into mathematical models and analytical modeling of consumer preferences should be integrated with the qualitative human-centered design principles to positively affect the design of products and systems. Because the design process inherently involves designers from many disciplines, a key design science topic area is communication and information sharing among diverse communities, together with a rigorous decision-making framework. Design science dealing with complex systems involves all aspects of design complexity, including interaction between people on the design team, organization structure, efficient process design, large-scale optimization of overall system performance, and decision-making under conflicts of interests.

Future design science research, in understanding the role of the human (both as user and as designer), will not only build on the fundamental principles of design but will also exploit new and exciting research opportunities in crowdsourcing, social computing, web-based user analysis, human-centered design, network analysis, data mining, and many other fields.

P. John Clarkson

Design processes produce designs. There is ample evidence to support this simple statement in the world around us. What is less certain is how to characterise the design processes that produce 'good' designs, where 'good' might convey the sense of being of a high (or at least satisfactory) quality, useful for some purpose (specified, implied or generally understood), worthy of approval and viable (within a given commercial or social context).

The study of design processes over many years has resulted in the creation of numerous descriptions of the process, ranging from the abstract 'Squiggle' (Damian Newman, https://revisionlab.wordpress.com/that-squiggle-of-the-design-process/) and simple 'Double Diamond' (UK Design Council, http://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond) to the more comprehensive 'Engineering Design Process' (Pahl, G., Beitz, W., Feldhusen, J. & Grote, K.H. (2006) *Engineering Design: A Systematic Approach*, Springer, ISBN 978-1846283185) and 'Total Design' (Pugh, S. (1990) *op. cit.*) models. Each provides different insights into the nature of the design process, typically based on the observation of a significant number of actual processes. However, again the question arises as to which of these, or indeed any of the other available process models, might assist in the delivery of a 'good' design.

Textbooks, websites, training resources, expert consultants and academic researchers all propose many frameworks, methods and tools to assist in the delivery of 'good' products. Yet, again the question arises as to which of these, alone or in combination, should be employed to best effect to create the plans for a product in response to a particular set of functional, behavioural, structural or aesthetic criteria, set in the context of inevitable resource constraints.

Companies and individuals develop their own models of design, from high-level Stage-Gate® methods and engineering systems approaches, through multiple layers of systematic and informal planning, to low-level working methods and codes, as a means to manage the inherent uncertainty and corresponding risk in design. Such methods and tools are often highly sector, company and product specific, representing a connected body of demonstrated truths and observed facts describing previous 'good' design practice. Other approaches derive their validity from practice across many sectors and products; for example, the 'V-model' highlights the merits of decomposition and integration in the delivery of complex systems, while design structure matrices provide a simple means to support both the analysis and the management of complex product architectures, organization structures and design processes. All try to codify some part of a collective 'science' of design within the design process.

After over twenty-five years of designing and researching the design process, it remains clear to me that engineers and designers, by whatever definition, are easily motivated to create something new, something 'good'; that successful design processes are characterized by the presence of appropriate levels of creativity, uncertainty, knowledge, rigour and management; and yet that many 'good' products still ultimately arise from 'poor' processes. We need to continue to ask what 'good' or 'better' or even just 'adequate', looks like and to continue to develop theories and practices of design that achieve an appropriate balance between product quality and process effectiveness.

Design processes produce designs. It is to be proven that 'good' design processes produce 'good' designs and, in view of the uncertainty that defines design, there remains a need to develop the science of design, '. . .a connected body of demonstrated truths or observed facts systematically classified and more or less comprehended by general laws, and incorporating trustworthy methods for the discovery of new truth in its own domain', i.e. current 'good' design practice.

Alex Duffy

Science can be considered as the establishment of a formal body of knowledge through the collective and systematic efforts of a community of researchers. Scientific research seeks to define the basic principles underpinning natural and artificial phenomena, generating knowledge that is applied to support and improve human activities (Simon, H.A. (1969) *op. cit.*). In a design context, improvements in design support and the design process *per se* are fundamentally dependent upon scientific models and theories about design (Duffy, A.H.B. & O'Donnell, F.J. (1999) 'A design research approach', in N.H. Mortensen and J. Sigurjonsson (eds), *Critical Enthusiasm – Contributions to Design Science*, Norwegian Research Council P2005, Norges Teknisk Naturvitenskapelige Universitet, Olso, pp. 33–40). Accordingly, a significant research community has grown around design science, which can be broadly taken as the scientific study of design and its methods, tools and artefacts.

Design science can contribute to a number of grand challenges facing the world, including climate change and environmental protection, aging populations, health and well-being, and sustainability, to name just a few. Gaining insights and developing a formal body of knowledge regarding design's role in meeting such challenges is a commendable endeavour. Focusing on the challenges for design science, the effectiveness of our efforts to establish a body of scientific design research may hinge upon our ability to overcome two key issues: (i) understanding the essence, the scientific basis, of design at a fundamental level and (ii) being able to integrate and coalesce such understanding.

Deeper knowledge regarding the scientific principles of design is needed in order to develop a body of fundamental design knowledge. Over the decades, increasing research in this area has been driven, at least partially, by a growing interest in artificial intelligence and its role in supporting the design process. Authors such as Herbert A. Simon (1996, *op. cit.*) recognised that replicating human intelligence through artificial means requires knowledge of the fundamental mechanisms and principles governing thought. Yoshikawa's general design theory represents an early contribution to design science in this respect, describing a designer's basic activity – regardless of discipline or specialism – in terms of a fundamental model of human intelligence (Yoshikawa, H. (1981) 'General design theory and a CAD system', in T. Sata and E. Warman (eds), *Proceedings of the IFIP WG5.2-5.3 Working Conference 1980*, Amsterdam, pp. 35–57). More generally, Simon proposed a 'science of the artificial': a formal body of knowledge about 'artificial objects and phenomena' that transcends different areas and disciplines. Today, a combination of social, technical and artistic research (STAR) is needed to understand aspects such as the neurological basis of design (Goel, V. (2014) 'Creative brains: designing in the real world', *Frontiers in Human Neurosciences* 8, 1–14. DOI:10.3389/fnhum.2014.00241), the basic physical and social principles affecting artefact and design process sustainability, and the phenomena governing user behaviour and perceptions (Bhamra, T. & Lofthouse, V. (2007) *Design for Sustainability: A Practical Approach*, Gower, Aldershot). As highlighted by Simon, 'a science of artificial phenomena is always in imminent danger of dissolving and vanishing' unless its basic principles are formalized. Establishing the scientific underpinnings of design is therefore critical for the cohesion and evolution of design science in the 21st century.

Gaining fundamental insights into design is not enough to establish a body of design science research. The integration and coalescence of the multi-faceted aspects of design is required. For instance, the concept of sustainability has broadened the scope of design to include the full range of lifecycle stages. Knowledge of manufacturing, operation, disposal and recycling considerations needs integration into design knowledge to support effective through-life decision-making. Design is expected to deliver innovative technologies to support human health and well-being, economic growth and environmental protection. Effective technological development in these areas requires the integration of knowledge from multiple disciplines, both within the design domain and beyond (Coley, F.J.S. & Lemon, M. (2009) 'Exploring the design and perceived benefit of sustainable solutions: a review', *Journal of Engineering Design*, 20, 543–554. DOI:10.1080/09544820802001276). Fostering the creativity needed to drive innovation also requires better design support, which must be founded in knowledge of the basic elements of design including people, processes and methods/tools. In addition to social and technical aspects, designing is artistic and creative in nature and involves elements such as sketching, graphic visualization and concept modelling. Thus, design knowledge needs to integrate artistic knowledge of elements such as form, colour and techniques such as sketching (Goldschmidt, G. (1991) 'The dialectics of sketching', *Creativity Research Journal*, 4, 123–143. DOI:10.1080/10400419109534381).

The challenge of establishing design as a science rests not only in developing fundamental knowledge of all aspects of design, but also in how we shall integrate and coalesce such knowledge.

Ashok K. Goel

The launching of the *Design Science* journal comes at an opportune time because the science of design is both maturing rapidly and transforming radically. In this article, I focus on two design movements indicative of this growing maturity and transformation. Although neither is new, it is only over the last generation or so that they have developed into important and widespread movements in design.

(1) The first design movement relates to human cognition, and thus I will call it 'cognitive design.' The cognitive design movement actually has two paradigms within it.

1(a) The first paradigm of cognitive design is quite well-established: it puts users of the products of design at the center of the design process. This paradigm is known variously as human-centered, user-centered, activity-centered, cooperative, participatory or contextual design, or sometimes simply as co-design. There are many conferences and journals devoted to this paradigm as it has already transformed the practice of design (Norman, D. (2002) *The Design of Everyday Things*, 2nd edition, Basic, New York).

1(b) The second paradigm of the cognitive design movement is nascent but starting to blossom: it uses our understanding of human thinking to address early phases of the design process such as design ideation and conceptual design (Simon, H.A. (1996) *op. cit.*). Much research on design since the advent of computing about half a century back, especially in engineering design, has focused on downstream tasks such as modeling and analysis, simulation and optimization, etc. Upstream design tasks such as problem formulation, design ideation and conceptual design have received less attention. However, this is beginning to change in part because of advances in cognitive science and artificial intelligence. On one hand, we are gaining insights into the fundamental cognitive processes of understanding, ideation, concept formation and creativity. Examples of these cognitive processes include analogical reasoning, i.e., thinking about novel situations in terms of similar familiar situations, visual thinking, i.e., thinking about images and thinking in images, and meta-cognition, i.e., thinking about one's own goals, knowledge and reasoning. On the other hand, we are building powerful artificial intelligence technologies for realizing these processes in computer systems and using them for supporting the early phases of design. These developments likely will transform design practice.

(2) The second major movement in design pertains to nature, and thus I will call it 'natural design.' The natural design movement also has two paradigms within it.

2(a) The first paradigm of natural design is quite well established: it views all designed products as parts of living, natural systems, and puts the environment at the center of the design process. This paradigm is known variously as ecological, environmental or sustainable design, or sometimes simply as ecodesign (Van Der Ryn, S. & Cowan, S. (1996) *Ecological Design.* Island Press, Washington, DC), and has several conferences and journals associated with it. As concerns about the health of the environment become increasingly critical and urgent, this paradigm is radically transforming design practice.

2(b) The second paradigm of natural design is incipient and burgeoning rapidly: variously called biomimicry, biomimetics, bioinspiration and biologically inspired design, it espouses the use of biological systems as analogs for designing technological artifacts as well as standards for evaluating them (Benyus, J. (1997) *Biomimicry: Innovation Inspired by Nature*, Harper Collins, New York). For example, the biochemical processes of additive fabrication provide biological analogs for designing innovative and sustainable manufacturing processes. The principles of the physical sciences, specifically the laws of physics and chemistry, are the foundation of all design, including engineering design. However, biology offers another set of useful constraints and affordances in the form of design principles and patterns that act as intermediate abstractions for generating and evaluating designs for technological artifacts. Biomimicry pertains not only to product design but also to the design of buildings, processes and systems. Biomimicry is useful not only at the meter scale, but all the way from the nanometer to the kilometer scale. Over the last generation the number of publications and patents in biomimicry has doubled every three years or so, and biomimicry is projected to become an 'economic game changer.'

I have been working on problem formulation, design ideation and conceptual design from the perspectives of artificial intelligence, cognitive science and human-centered computing for about three decades. Much of my work has focused on developing computational theories, techniques and tools for within-domain and cross-domain analogical design (Goel, A. (1997) 'Design, analogy and creativity,' *IEEE Intelligent Systems, Special Issue on AI in Design*, 12(3), 62–70). Over the last decade, I have investigated analogical design in the context of biomimicry because of its promise to impact creative design as well as sustainable design (Goel, A., Vattam, S., Wiltgen, B. & Helms, M. (2012) 'Cognitive, collaborative, conceptual and creative – four characteristics of the next generation of knowledge-based CAD systems: a study in biologically inspired design,' *Computer-Aided Design, Special Issue on Next Generation CAD Systems*, 44(10), 879–900). It is noteworthy that the concepts and methods of analogical design and biomimicry are applicable to almost all design disciplines and domains. Thus, it is exciting to be a part of the *Design Science* journal devoted to interdisciplinary design research.

Sean Hanna

Design Science may appear to be a contradiction in terms. Design and science are two disciplines typically separated by institutional boundaries, and for those in either camp, it might seem that one cannot really do both. The aim of science is to state how the world is, and its statements are at best both simple and true in general. Design, by contrast, deals with the complexity of what might become of a one-off situation in all its particulars. Science relies on the repeatability of results among colleagues conducting experiments in the laboratory, whereas design celebrates the lone genius, the very word 'design' coined from Rennaissance and Enlightenment ideas of the guiding intelligence as opposed to the hands-on craftsperson or builder. Most of all, where science requires clarity of rational thought, design celebrates the innovation of creative intuition, with all its potential vagary. So what can science really teach us about design?

For all their differences, the two disciplines probably share more similarities. Science is obviously creative in its big paradigm-changing revolutions: we acknowledge this in celebrating the genius of a Newton or an Einstein. But the everyday creative processes are also similar. The testing of hypotheses in science (as observed by, e.g., Karl Popper) is fundamentally a social process, among different people, who may have different observations, but eventually agree on a single theory. Design practice (as observed by, e.g., Donald Schön) involves constant criticism that tests design proposals by similarly involving many people, with different views, and the design evolves in this way. Even the lone designer sketching on a napkin progresses by constantly proposing different views of the sketch. The actual processes of science and design are analogous.

Herbert Simon was explicit in this when he called design the 'Sciences of the Artificial.' For many design methods theorists of the twentieth century, design could be clarified to the extent that its methods could be known, taught and even automated. This position provided a clear foundation for design research, but it has since been resisted by many practicing designers. They had good reason to do so: we can do this, to an extent, but only for the relatively easy parts of design. Just as the major twentieth century philosophers of science (like Thomas Kuhn and Karl Popper) left the mystery of how the mind actually conceives of a new theory or hypothesis unexplained, design theorists (like Christopher Alexander and Herbert Simon) also left the central mystery of how one translates the complexity of reality into its clear representation. Both of these are really difficult and important questions.

While science and design are similar, it is not because design can be made as clear as we believed science to be, but that the creative processes that are really at their heart are both messier and more complex than we may have thought. Decades of research indicate that this is the case in the mind of the designer and decades of practice highlight the inadequacy of rigid processes, simple combinatorics, etc.

We do not yet fully understand this process, but we might have reason to think we are getting closer. Our vastly increasing computational power and access to data are not just technical changes, but changes in how we can see the world. They have radically changed the sciences in making complexity understandable, and they are doing the same for design. The computational paradigm in which Simon worked 50 years ago was very different, in that intelligent processes – even those of the human mind – had to be seen as clear, symbolic manipulation because this was the limit of what the machine could do. This is no longer the case. The advent of machine learning, big data, parallel processing and similar computational tools on one hand, and the technology to see brain activity on the other, provide the tools both to model and to observe this messy process. The activity of design involves insight, creativity, planning, communication, and potentially all of the cognitive distinctions that make us human, and, more than any other activity, its effects literally change the world. If these tools really allow us to understand this process, the science of design may be among the most important sciences we have.

Yan Jin

Design is a human activity of identifying purposes and developing concepts and realizations of artifacts that achieve the purposes under various environmental situations. Depending on the types of artifacts, design has been categorized into various disciplinary areas, such as engineering design, architectural design, industrial design and fashion design. Different design areas have different concerns; some are function driven, and others aesthetics oriented. From a research point of view, engineering design has made significant leaps in the past two and a half decades in the broad areas of design cognition, design computing and optimization, and design for lifecycle and sustainability. Specific progress has been made in design ontology, design creativity studies, design decision-making, design knowledge modeling, bio-inspired design and design of complex systems. Design communication, including gesturing, and collaboration have also attracted researchers' attention. Although it is still arguable whether design science exists, and design research is still fragmented among different design areas, the research to date has provided a solid foundation for future research in design science.

Herbert Simon in his seminal book (Simon, H. (1969) *op. cit.*) suggested that 'the proper study of mankind is the science of design.' He further indicated that such a science of artificial phenomena 'is always in imminent danger of dissolving and vanishing,' because 'the peculiar properties of the artifact lie on the thin interface between the natural laws within it and the natural laws without.' The challenge for the community is how to enrich the interface and make it 'thick and strong.' This can be done when design science as a field not only stands on its own but also informs other fields, e.g., cognitive science, computer science, biological science, complexity sciences, just to name a few. Given that design itself is an interdisciplinary field, there are opportunities. A behavioral–physical paradigm can be explored for design research in the future.

Design can be viewed as interplay among purpose, artifact (inner) and environment (outer) carried out by a designer (behavior) in the context of natural laws (physical). The 'behavioral aspect' is determined by both the sociological and psychological background of the designer or designers in a design team. A deep understanding of designers' thinking process of generating purposes, alternatives and making decisions under various sensory and mental influences is needed as a basis for the behavioral part of design science. Common behavioral properties for all design areas can be expected. In addition to observational behavioral studies, computational simulation based design thinking research will likely play an important role in the near future. Since designing can be an emotional behavior in general, effect-based design thinking studies will be needed especially when industrial design and fashion design are considered. On the other hand, the 'physical aspect' of design deals with the 'thin' interface between the artifact and the environment. New technologies contribute to the artifact's 'inner nature.' New requirements, such as sustainability laws, embody the environment's 'outer nature.' Future research needs to explore new ontological concepts, reasoning logic, fundamental principles and computing algorithms in order to create and maintain the balanced mapping between purpose and artifact, and artifact and environment. An established behavioral–physical design framework should provide physical vocabulary and tools for composing artifacts as well as behavioral training and tools for designers to achieve most effective and efficient design thinking. Furthermore, the results should inform and help other relevant fields.

Yong Se Kim

Design is to conceive and to make artifacts within the constraints of nature, the human and society. The objects of designing artifacts can be in the form of products with physical properties or in the form of services with human activities, as well as in the form of integrated products and services. Design research today and in the past has dealt with designing of products much more than of services. Obviously, we make products for humans to improve their lives, but often the use activity of humans has not received enough attention. Ideally, it should be the other way. The fields of service design and product–service systems design are much younger ones in design science research. Even in design practice as well, they are less mature. This status of today should change in the coming days as things exist for human activities. With technological advancement in product provision, there could be many different ways to provide things once human activities are well designed.

To provide desirable human experiences, service elements to address individual preferences of human and product elements to enable smooth and natural human activities need to be designed jointly. For example, an Internet of Things would enable human activities or services designed to drive active emotional values. More active design research on services and product–service systems is expected in the near future.

While the objects of designing dealt with in design research should be expanded to address services and human activities, design research should address design methods and tools to support design practice. Asserting the importance of basic principles and key phenomena is necessary, but practical methods to design for such important aspects should also be devised. While the importance of affordances, for example, has been emphasized for some time, practical methods and tools for the design for affordances have not been devised until recently. Design methods and tools at various stages of designing should receive continued attention in design research of the future. This is to make sure that the research world is always connected with design practice. With similar concerns, design education should continue to receive great attention in design science research. As many people agree these days, the impact of design is increasing and the boundaries of designing are broadening. Compared with these changes in practice, education has not gone through significant reformations yet. More comprehensive research should be done in devising design education innovation.

Terry Knight

At my home institution of MIT, 'design' is in the air. New courses and programs in design, from freshman recruitment courses to master's level degree programs, have appeared in the last few years. In the architecture department where I reside, we are considering a new minor in design for students across the Institute, which may evolve into a new major. Design is increasingly identified as an activity that is integral to work in diverse disciplines, from management to engineering to the humanities to architecture to media arts and sciences and more. Moreover, within a discipline, design is increasingly recognized as entailing some synthesis of best practices and pedagogies from outside fields. This growing interest in design at MIT parallels trends at other educational institutions and in industry, too, with the emergence of new design-centered companies and expanding in-house design teams in leading corporations.

The attraction to design stems in part from the perceived potential of some traditional, time-tested qualities of design, particularly as it is practiced in architecture and the applied arts. These qualities are being looked at anew for contemporary technologies and new contexts. They include interrelated qualities such as

- *doing/sensing*: direct, hands-on, perception/action-based work;
- *playing*: improvisational, experimental, risk-taking processes that embrace unpredictable, emergent conditions;
- *making*: quick, iterative idea development and production through prototyping and material exploration;
- *easy access*: easily accessible (often low-tech) methods of working;

- *collaboration*: working with others, sharing ideas and resources;
- *situatedness*: sensitivity to the social, cultural, and historical contexts for design.

Of all of these, the rising interest and activity around making is most notable. Some, including me, are rethinking designing–making relations to propose making as an umbrella concept that would include designing.

The launch of the *Design Science* journal is a timely response to widening interest in design. Other journals already exist that advance design broadly. *Design Studies* and *Design Issues* are two excellent examples. This new *Design Science* journal is dedicated, in particular, to promoting cross-disciplinary conversations about design.

About 'design science' – in the spirit of Nigel Cross's (Cross, N. (2001) *op. cit.*) distinction, I interpret this phrase to mean the science – or study – of design, as opposed to design as a science or as a scientific enterprise (a narrow idea). Herbert Simon has probably had the most profound influence on how we understand the scope of design and how it might be studied, practiced and taught. His ecumenical, 1969 definition of design as 'courses of action aimed at changing existing situations into preferred ones' (Simon, H. (1969) *op. cit.*) set the stage for our current broad-based understanding of design. His related call for a 'science of design' was ambiguous in some ways, referring at times to research on the design process, at times to the design process itself, and at times to a theory of design. However, his main message was clear – design can be and should be rigorous, and rigorous on its own terms. Rigor in design is different from rigor in the natural sciences. Design, as Simon put it, should be 'intellectually tough, analytic, partly formalizable, partly empirical.' The word 'partly' here is key and mostly ignored. It reveals the nuances in thinking about a science of design. His science is one that acknowledges and respects the messy, indeterminate complexities of real-world design problems, the difficulties of relying on pre-cooked design strategies, and the need to make on-the-fly decisions and changes – all of these not unconnected to the features of design mentioned above.

Simon's and others' early contributions to the study of design opened the door to the rich variety of differently rigorous approaches – empirical, experimental, mathematical, computational, philosophical, ethnographical, and so on – to the study of design today. As for the future? I think (I hope) that there may be more effort to research and find ways of integrating the wonderfully distinctive, traditional features of design (outlined above) with new technologies and resources to advance design as a singularly fertile and productive territory.

Udo Lindemann

Engineering design is and was dealing with the future, especially when it is not done for a specific customer! This is one of the important arguments to shorten the product development time. Other arguments are the cost or competitors or technologies. Markets (customers, sub-suppliers, custom and law situations, exchange rates, etc.) are changing with increasing speed. All of this leads to pressure on product development to be fulfilled in shorter time (faster, parallelized), robust (reduced risk) and transparent (for operation as well as management) in different dimensions (quality, cost, etc.).

The market lifecycles of technical products differ from less than two years (smart phone) up to around a hundred years (water turbines, ships). The lifecycles of technologies differ again between several months (some electronics, sensors) and years or decades (gears). Solutions are required to solve the different cycles of technologies within upcoming products or those in interaction with these upcoming products like production or communication.

New and different business models like PSS (Product-Service Systems) are coming up. Not the classical product (car, compressor, printer) but the generated outputs (mobility, compressed air, printed sheet) are sold to the market. This will change the whole chain of value creation including product development and has the potential to support sustainability.

The digital world offers new possibilities (communication, Internet of Things and Services, additive production, big data . . .) and threats (piracy, efforts for security and protection of knowledge . . .). These and all the above points ask for more knowledge about the interdependencies, the meaning of structural patterns and the dynamics based on that. Better understanding and transparency are the required basis for good decisions as well as goal-oriented creativity.

Product development is based on the cooperation of several disciplines. The number of involved disciplines will increase in the future, when we move more and more into the Internet of Things or integrated 'intelligent' capabilities of products. In addition, product development has become global, again a demanding point of cooperation. The development and improvement of one or at least a few common platforms of modeling and modeling languages like SysML is required for exchanging information and joint product development. In addition, cooperation has to be supported also by specific skills.

Employees are changing their habits and expectations over time. Demographic changes in a relatively short time have an impact too. The individual importance of a career and the boundary conditions of private life are changing too (both parents working and the significance of holidays or other aspects), which has an impact on industry. Actually, the industry in mechanical engineering tries to involve more female staff as well as keeping older people within the process. Based on all of these changes the structure within product development will change; there will be a move to other or at least additional organizational forms.

Design research has to generate and develop the scientific basis for all of these demanding topics including all the interdependencies in a holistic way; it must be

- open for new and creative ideas and thoughts, and foster these;
- rigorous but also allow experiments and report not only successful results but also failures;
- of relevance for science itself, for industry and economy, for society and humanity and the environment.

Jordan J. Louviere

My expertise is in understanding, modeling and predicting (forecasting) human decision-making and choice behaviour. I do not design things, nor do I participate in the design of things (except occasionally and by accident). However, I have a deep interest in the outcomes of designs and design processes. Over the last 30+ years I have participated in many projects with the objective of forecasting the demand for (i.e., uptake of) and willingness to pay for changes to existing product and service configurations and/or new-to-the-world products and technologies across a wide array of product and service categories ranging from aeroplanes (e.g., the B787) to zoological preservation proposals (e.g., Woodland Caribou in Alberta). I developed the original theory and methods known as Discrete Choice Experiments (DCEs, or more recently, Best–Worst Scaling, Case 3) now routinely used by many companies and government agencies around the world to meet this objective (e.g., Louviere, J.J., Hensher, D. & Swait, J. (2000) *Stated Choice Methods: Analysis and Application*, Cambridge University Press; Louviere, J.J., Marley, A.A.J. & Flynn, T. (2015) *Best–Worst Scaling: Theory, Methods and Applications*, forthcoming, Cambridge University Press).

During that time I worked with many companies dominated by IT and engineering groups who routinely developed 20–50 or more designs that were launched, with the expectation that perhaps 1–2 would 'succeed' (always arbitrarily defined). I also worked with companies that were convinced that they really did not need advanced market information because they 'led' the market. The popular press is fond of highlighting such companies, but the ones that succeed in this approach over long periods of time are few and far between. And, quite frankly, it is time to end the practice of somehow believing that one or a small group of persons somehow has the 'secret sauce' and will always succeed. The Nobel Prize was awarded in Economics to finance researchers who conclusively proved that no one could consistently beat or time the market, yet many continue to believe that there are 'special people' out there. It is not true for finance and it is not true for companies. Indeed, I have been studying how well managers in real companies actually understand the choices that their customers make since 1984, when I showed the CEO of a large resource company that his sales staff not only did not know how customers made choices, but they consistently did things the customers did not like. After retraining the sales staff, the company shot to number three in the industry in one year and was acquired by the industry leader shortly after. My observation that managers do not understand customer choices has not changed since 1984, which includes a cross-section of companies and government agencies.

Thus, I conclude that humans need all the help they can get to understand markets and the customers in them. This is especially true of rapidly changing or new and emerging markets. I like to describe the problem with the table below. Despite all the hype, so-called 'big data' largely applies to current products in current markets, with the possibility that real-time and/or quasi-continuous updating could provide feedback about markets where data are available. For cases involving new products in new markets, there are by definition no data available; hence, there is a clear need for theory and methods that can help us to better understand and predict these cases. Currently, best practice for these cases involves designing controlled experiments that use multimedia and other technologies (e.g., gaming and simulation) to simulate likely futures, market evolutionary paths and future product configurations offered at different prices, competing with different potential subsets of competitors. By observing the likely choices (i.e., purchases and/or purchase quantities) under various controlled conditions, one can develop models that allow forecasts to be made under a wide array of possible future scenarios, product configurations and prices (e.g., Urban, G.L., Weinberg, B.D. &

Hauser, J.R. (1996) 'Premarket forecasting of really-new products', *The Journal of Marketing*, 47–60).

		Markets	
		Current	New
Products	Current	Data available (i.e., 'big data')	Few, if any, data available
	New	Few, if any, data available	No data available

Thus, we clearly can do better than guessing and/or insisting that we 'know' what the market wants and/or what is best for consumers. Therefore, my hope is that this editorial will encourage designers and design scientists to think about the fact that their current ideas may not be the best for the market, that we can in fact model likely future choices and identify which product configurations at which price points are most likely to succeed (if at all), we can identify likely potential segments in such markets that are more likely to choose particular product configurations and prices (there is rarely a 'one size fits all') and, when combined with reasonable cost estimates, we can also model and predict likely future revenues and profit margins. It seems reasonable to me that good design science and practice should go hand-in-hand with good future market forecasting science and practice. I look forward to seeing that happen.

Chris McMahon

Design research has come a long way since Herb Simon wrote of the desire for a body of work that is 'intellectually tough, analytic, formalizable, and teachable.' Good understanding has been developed of the nature of design and of design thinking, underpinned by the development of a sound theoretical foundation in design theory. Novel arrangements of design elements can be proposed in innovative product and systems architectures, and the rules and constraints governing the arrangement of such elements are well understood. Modeling to support design analysis and synthesis, especially computational modeling, is ubiquitous. Design for many aspects of the lifecycle (the 'ilities') is well documented (although the range of 'ilities' that is comprehensively covered is limited). A very wide range of teachable methods and tools is in place. In the organization and management of design, design processes, risk and uncertainty management, and design decision-making have all been comprehensively researched. The behavior of designers and users of artifacts has also been widely researched such that consolidated material can be presented on subjects as diverse as risk perception, creativity, cultural issues in design, team behavior and design for emotion. Moreover, this list of achievements is of course only a partial one!

However, while great progress has been made in advancing our understanding of design, there is still enormous progress to be made, especially if we are to be able to achieve the rates of change required to tackle the challenges of the 21st century. First, most design knowledge is proprietary – it is held by the organizations that design our products, services and systems. In consequence, it is difficult to teach or learn many aspects of design except in the context of practice in such organizations. We need new ways to capture, document and disseminate design knowledge. Second, although an enormous number of design methods and tools have been developed, the total domain of possible design problems is only incompletely covered and the problem space is poorly categorized. We need to improve our understanding of the gaps, and, where we have methods, to better match problem to approach. Third, when we stray very far from cases that we know and understand, our tools are often too uncertain to be trusted. The consequence is that novel designs often need very extensive and expensive testing. The issue is again one of proprietary data and of accumulating and sharing engineering knowledge, but it is also a 'big data' challenge – how can we learn from the very extensive data that we have about the performance of artifacts and the tools used to design them? Fourth, we have a poor understanding of the cost and time implications of novelty in the development of products, systems or services. As well as having the tools and methods to propose novel concepts we need to be able to advise on the time and resource implications of realizing these. A consequence of all of these challenges is that novelty in design is expensive and risky to bring to practical fruition. Therefore, at a time when we need novel solutions to address global challenges, we concentrate our efforts on existing dominant designs into which we are locked, making incremental improvements but not overcoming the real challenges that are faced. Much of our current research has been about making these incremental improvements. For all of our futures we need to learn new ways of designing, and to inspire our societies to be bolder in their ambition for change.

Yukari Nagai

Design is a crucial phenomenon because it is an actual expression of human creativity and its result. Our society is but the result of human creativity, designed or otherwise. We expect design science to be different from other science: it must have a holistic nature and structure within a specific time scale. We must form the design discipline as a comprehensive academic discipline encompassing the creativity and knowledge of human beings. Thus far, design science has been challenged to integrate some interdisciplinary, basic approaches such as systems science, cognitive science, computing science and engineering science as a way of overcoming the limitation of scientific fundamentalism. To form a new paradigm of design science, the discipline must reach beyond mere accumulation of discussions and study of design activity or research on engineering or product design.

I would like to address the features of the approach to design science.

(1) Long-term time frame

Design by itself is meaningless, for who can design without dreaming of the future? That is to say, the essence of design is synchronized with the power to think of the future (Taura, T. & Nagai, Y. (2013) *Concept Generation for Design Creativity: A Systematized Theory and Methodology*, Springer Verlag). Hence, we should carefully consider what time frame constitutes the future. In daily life, people regard the future with a very limited time frame – anything from minutes to years. Design skills relate to the cognitive limitation of time. In professional design work, regardless of domain, the ability to foresee at least a half century or longer is essential, depending on the object. In special cases, design involves creating the future by targeting a very distant world, one that lies hundreds, thousands or millions of years away. Design science includes such special cases because of the need to understand comprehensive human creativity that can be channelized into large-scale projects that span longer periods than general engineering. Such a long-term view of the time frame is feasible for overcoming the effects of cultural differences as well as any political or economic bias surrounding human creativity.

(2) Essence of creativity

The core mechanism of design thinking can be investigated by examining human cognitive processes through experimental study. However, experimental study has inescapable limitations in driving the real passion of design given that it is situated in an objective framework (Roy, J.M., Petitot, J., Pachoud, B. & Varela, F.J. (1999) 'Beyond the gap: an introduction to naturalizing phenomenology,' in *Naturalizing Phenomenology*, Writing Science, Stanford University Press). When we consider the essence of creativity, an obvious fact is that self-motivation and gaining knowledge in creative thinking are human traits, that is, the formation of self (Sano K., Nagai, Y. & Taura, T. (2009) 'Poietiques based method for self-investigation of the creative processes in design,' in *Proceedings of the International Association of Societies of Design Research*, CD-ROM, Seoul). Design involves creative thinking that particularly accelerates the formation of self. Therefore, in order to challenge an internal observation to identify the essence of creativity in design through self-formation, the development of feasible methodology in design science is key.

(3) Criticism and interplay

'Design scientists' will be able to provide an independent criticism of the designed products and offer suggestions about the value of such products for future society. Moreover, design scientists should not be isolated from actual society but instead be encouraged to interact with designers, engineers, technologists, management and end-users so that they can be motivated to bring about valuable social innovation. The attitude of design scientists could perhaps change scientific process.

Yoram Reich

Instead of predicting the future of design science, let us design it. The ideas here have been articulated in part in previous editorials (e.g., Reich, Y. & Subrahmanian E. (2013) 'Editorial, Philosophy of design, science of design, engineering (of) design: what is your choice?,' *Research in Engineering Design*, 24(4), 321–323).

Over the last 100 years many people have occupied themselves with design science. For Gropius, the founder of the Bauhaus, design science was a means to achieve his goals. Buckminster Fuller's idea of design science was '. . .the effective application of the principles of science to the conscious design of our environment in order to help make the Earth's finite resources meet the needs of all humanity . . .' (Fuller, original source unknown). In order to make it a reality, in 1965, Fuller inaugurated his 'World Design Science Decade' with the goal of making better use of the world resources to help humanity. Fuller's design science program and its content and tools were set to achieve his goals.

Herbert A. Simon considered design science to be a body of knowledge about design. In a period of half a century, design science moved from a pragmatic entity (Gropius, Fuller) to a scholarly activity having its own merit (Simon). Cross proposed to distinguish between these two positions, pragmatic and scholarly; the first would be called science of design and the second design science, but this distinction did not catch on.

If we wish to call what we do science to gain legitimacy or for any other reason, so be it; however, science is no more considered as an idealized human activity that observes nature and formulates laws about how nature really works. Scientists are not those who influence society most – the innovators are. Therefore, it seems unproductive to debate what we call our activity and what its nature is.

Rather, instead of predicting the future of design science, let us design it – a paraphrase to Dennis Gabor's statement 'The future cannot be predicted, but futures can be invented' (Gabor, D. (1963) *Inventing the Future*, Secker & Warburg). Note that Gabor invented holography and received the Nobel Prize for this invention in 1971. Clearly, he did not study natural phenomena but invented a new one. He was not a scientist, but an electrical engineer whose goal was to extend the scope of engineering and to use innovations to solve technical and social problems. We should decide what the purpose of design science is, and design it to satisfy it. It is thus my contention that contributions to design science must clearly detail what they view as the purpose of design science. Subsequently, they should put forward a hypothesis that moves us forward to attaining this purpose. The relation between the hypothesis and their purpose of design science should be clear and acceptable. Finally, the methodology of the study should be defended as supporting the research hypothesis. To illustrate, if the goal of design science is to advance design practice, including the design of large-scale systems, a study of teams with five designers is irrelevant. Such a study is warranted if the authors describe a realistic design project that can be represented by the study set-up; if they claim that design science ought to help to improve this practice, their experimental setting should provide conclusive support for their hypothesis, and they need to limit the applicability of their results to this scope and suggest how it can fail. With such approach to design science, we will not waste time arguing about whose design of design science is better, but we will deal with what constitutes good design research that advances its stated goals. In designing design science, we will also be using the design tools we develop in research; we will thus practice what we preach – another benefit of my position.

Colleen Seifert

'Design science' is a compelling combination.

Design in its many forms is ubiquitous in the world today, and increasingly important to sustaining life on our planet. As individuals, we appreciate good design, and respond to it by choosing it above alternatives. We are moved by design, and are inspired to design our own life spaces. Design can be so beautiful, and so breathtaking, that it inspires true 'awe' in its audience. But what do we know about how good design is created?

Many view innovative design as ineffable, a mystery, a 'gift from the gods.' Designers often cannot tell us (at least, not accurately) about the influences on their design process, and the sources of inspiration for their ideas. Where do great ideas come from, and how do novel concepts come to fruition? What processes take place within the mind, and between minds working together, that bring a truly innovative idea into corporeal existence?

To answer these questions, the enterprise of design must go 'under the microscope': we need the tools of scientific inquiry to understand what happens in a successful design process. Using the methods of science, we can make systematic observations, test interventions and draw conclusions about the factors influencing design. Just as in practical domains like psychology, medicine and ecology, we can examine 'design' as the *object* of science.

By turning the lens of science towards designers at work, we can learn more about design, and about how to make good design more likely to happen. The mystery around design can be dispelled through science, and lessons learned can serve as a blueprint for improving design outcomes and training future designers. Science in its many forms, conducted on varied aspects of design practice, promises to lead to a greater understanding of this most important human enterprise.

Design science can tell us what leads to good design, and how to help individuals, teams and organizations to create the best designs possible. We can study designers at work, in natural environments and in complex teams and organizations, and draw conclusions about its nature. In the new field of design science, it is critical that we intentionally sample a rich variety of design activities, and select appropriate scientific tools to identify key factors in design practice. By doing so, we will advance the art and practice of design through greater knowledge about design gained from science.

Thus, design science is a key turning point in our understanding of the ontology of design. It stands to advance the art and practice of design by going beyond an intuitive appreciation of design to identify its essence. Through the science of design as a discipline, we will achieve a deeper appreciation for all that contributes to good design, along with the knowledge of how to foster it. Given the challenges facing humankind in the world today, the science of design may be the most important enterprise to pursue.

Steven M. Smith

Where do ideas come from? One answer is that ideas come from minds, human minds, which are the engines of creative design. The scientific study of the human mind is the purview of cognitive psychology; thus, the design community has a significant interest in the science of cognitive psychology.

Creative Cognition: Cognitive psychologists study cognitive structures and processes, typically, those that are universal among all humans. The creative cognition approach to the study of creative design takes the position that there is no special creative cognitive process that yields creative ideas, but rather there are many common cognitive processes (e.g., perception, visualization, abstraction) and structures (e.g., working memory, semantic memory) that can collaborate in myriad ways to generate creative ideas (Smith, S.M., Ward, T.B., & Finke, R.A. (1995) *The Creative Cognition Approach*, MIT Press, Cambridge, MA). This creative cognition approach views cognitive operations as analogous to the members of a creative team, such as a band or a symphony orchestra; although each participant has certain specifiable qualities, there is no limit as to the number or variation of products that can be generated by their collaboration. The creative cognition approach suggests ways of improving creative design, metrics for assessing designs and design processes, and even ways of testing and evaluating future designers.

Beyond Design Fixation and Analogy: The past 25 years of research on creative design have shown the useful role of cognitive psychology. Hundreds of articles have been published on design fixation, a tendency for designers to adhere to known or recently exemplified designs in spite of their attempts to be novel and innovative (Jansson, D.G. & Smith, S.M. (1991) 'Design fixation,' *Design Studies*, 12, 3–11), and structured imagination (Ward, T.B. (1994) 'Structured imagination: the role of category structure in exemplar generation,' *Cognitive Psychology*, 27(1), 1–40), the similar notion that creative ideas tend to adhere to known conceptual structures. The way that analogical thinking can inspire new creative ideas also has been the subject of a great deal of research in creative design (e.g., Goel, A. (1997) *op. cit.*). Such research highlights the fact that considerations of human cognition can provide insights into the nature of creative design. Design science must continue such research, as well as explore the role of other types of cognitive operations in creative design, such as conceptual combination, divergent thinking, remote association, visual synthesis, cognitive restructuring, insight, intuitive guiding, incubation and induction, to name just a few.

Putting Science in Design Science: For design science to be a true science, it should use the scientific method. The scientific method involves an iterative process that includes theories or explanations, testable hypotheses derived from theories, empirical tests of hypotheses, systematic analyses of the observations of empirical tests, and evaluations of theories based on the observed results. Too often design research takes the form of *I wonder what would happen if we did X?* Although such studies can be interesting, it is difficult to build a science of design from a haphazard, bottom-up collection of intriguing observations. Science is driven by testable (i.e., falsifiable) theories.

In scientific terms, a *model* is a theory, an explanation of something. Too often, designers try to explain everything important in creative design with a single unified 'model of design.' Although there may be a place for such unified 'models of everything' in design, these models tend not to be scientifically testable; that is, they cannot be proven right or wrong by any conceivable set of observations. Researchers must also focus on narrower, more constrained models, particularly models that make scientifically testable *predictions*. Design science should be driven by tractable theories and models that explain what has been observed, and that predict what will be observed if the models are valid. Especially because it is such a young discipline, design science must make progress by becoming a true science.

Mitchell M. Tseng

Design starts with users by finding their needs and ends with users by delivering to meet their needs. Users are well intertwined with their experience, their preferences with their perceived context (Nam, S. (1990) *The Principles of Design*, Oxford University Press). Successful design of products is very much dependent upon the clarity and completeness of the understanding of a customer's needs imbedded in users' experience. With the emerging social and technological trends in putting more emphasis on satisfying human needs, users' role in design becomes more significant (Wang, Y. & Tseng, M. (2014) 'Incorporating tolerances of customers' requirements for customized products,' *CIRP Annals – Manufacturing Technology*, 63(1), 129–132). Thus, product design has gone beyond the traditional objective of attaining monolithic functional requirements to meeting the ultimate goal of customer satisfaction.

Inclusion of users into the product design has many research challenges; to name a few, it encompasses the following.

Characterizing users' needs: Design needs to include consideration of user experience and user context with user cognition. They often can be expressed in the form of user preference embedded in different perspectives. The issue of describing the user needs in scientific terms that can be unambiguously characterized can be found in literature such as marketing research, human–computer interface and interactive design. It remains an important issue for the design process to elicit user needs, to measure the effectiveness and many others.

Incorporating users into the design process: There have been several methodologies developed and used to incorporate customer needs, such as focus groups, quality function deployment (QFD), conjoint analysis, etc. Most of them can serve in situations where users' needs are statics. To capture the user dimensions of experience in order to measure and translate into analyzable data, affective engineering/Kansei engineering has been proposed to create new attractive products and service with a profound affection for users. Product ecosystem has also been considered as the kernel of user involvement, to include a discussion of different prospective areas of research to help bridge between current prevailing design approaches and design for user experience. With the entry barrier reduced in both user needs elicitation at the front end and product delivery at the back end, other design approaches, such as open design and crowd design, have been proposed (Chesbrough, H.W. (2003) 'The era of open innovation,' *MIT Sloan Management Review*, 44(3), 35–41).

Dichotomy of individuality and scale of economy: Users often need to be considered as individuals, particularly in the recent trends in customization and personalization. However, there is an economic reality in economic scale in fulfilling cost, specifically in manufacturing, services and training. The balance between the value of individuality and the cost advantage of economic scale becomes an issue that cannot be ignored when we are addressing the users and user requirements.

Adaptability of users: Last but not least, the same product may have to serve different users. Even if the product remains with the same user, users may grow through the product lifecycle as time progresses. Users may also have a different set of scenarios to accommodate. Properly matching needs with users can also be an interesting research issue for product adaptation, particularly when product designs need to respond to the issues of sustainability. Incorporation of long-term requirements into changing needs can also be an important issue to address.

Pieter E. Vermaas

From a societal and academic point of view it seems obvious to me that design research develops to a science of design. Design research is a flourishing discipline that studies human activity in relation to our physical world, just as medicine does. And as this latter discipline is nowadays squarely taken as a science, so can design research. Moreover, just as medicine, design research generates knowledge that is directly relevant for our well-being and survival; hence, reason enough to require that design research proceeds with scientific rigour.

In the design research community there is hesitancy against this development and a preference to contrast design research with existing sciences. For instance, Cross (Cross, N. (2006) *op. cit.)* talks about designerly ways of knowing that define a 'third culture' different from the other two cultures of the natural sciences and humanities. Frey and Dym (Frey, D.D. & Dym, C.L. (2006) 'Validation of design methods: lessons from medicine', *Research in Engineering Design*, 17, 45–57) argue that for validating design methods design researchers can adopt some but not all of the research methodology part of medicine. Moreover, Koskinen et al. (Koskinen, I., Zimmerman, J., Binder, T., Redström, J. & Wensveen, S. (2011) *Design Research Through Practice: From the Lab, Field, and Showroom*, Morgan Kaufmann, Waltham, MA) present research-through-design as a practice that need not meet the criteria of research in the natural sciences or humanities.

These contrasts do not undermine the development of design research to a science but imply that design research is a new arrival to science. And, as a new arrival, design research need not be squeezed into the formats of existing sciences, but may find its own place as a science. This process includes giving contrasts with the natural sciences and the humanities but should continue more constructively by, e.g., determining what (alternative) criteria single out good design research and what (alternative) methodology validates its knowledge claims. In that sense, design research is now in the position the humanities were in when they found their place in science: resisting assimilation into the then dominant paradigm of physics, and specifying in what sense the humanities are sciences.

The work involved in specifying how design research is a science may explain the hesitancy within the design research community. In recent efforts in the Netherlands to give quality criteria for academic design research, architectural researchers argued that the prevailing criteria in science, such as peer-reviewed publications, did not apply to their research (Van der Hoeven, F. (2011) 'Mind the evaluation gap: reviewing the assessment of architectural research in the Netherlands', *Architectural Research Quarterly* 15, 177–187). Such an argument allows a retreat to adopting the existing quality criteria for architectural research, e.g., exhibitions, and avoids an analysis of what scientific rigour would mean in architectural research. For the design and engineering disciplines, separate quality criteria were instead rejected and it was argued that design research can be assessed with the existing generic scientific criteria of research quality and societal relevance (KNAW (2010) *Quality Assessment in the Design and Engineering Disciplines: A Systematic Framework*, Royal Netherlands Academy of Arts and Sciences Advisory Report, TWINS Council). This second effort approached design research as scientific, and then focused on the consequences of doing so, leading to further work in defining the content and relative weight of these criteria for each design research discipline, and to a plea to promote in design research a culture of peer-reviewed publications.

The hesitancy to take design research as a science may also be related to a fear that it further turns the activity of designing into a scientific one. The contents and methods of the natural sciences, technical sciences and humanities have already found their way to designers. If design reasoning and its methods become scientific also – so may be the reasoning – not much room seems left for creativity and innovation. I think that this is a valid point that should be discussed. Doing design research scientifically does not turn designing automatically into a scientific activity, just as studying riots sociologically does not make rioting a science. However, there is a choice about what to do with this knowledge. Given the societal interests and risks in food, sustainability, aerospace and nuclear industry, designing in these areas, whenever possible, should be based on scientifically rigorous knowledge. However, as it is not wise to fuel rioters with the latest insights about their activity, it may not be helpful to creativity and innovation to turn designers in areas such as architecture, product development and social design into fully scientifically proceeding designers.

Kristin L. Wood

Of all of the concepts, theories and content that are considered to comprise academic and professional pursuits, such as engineering, no subject is more pervasive and, perhaps, enigmatic than design. Design represents the bridge between theory and reality. It is the process by which our ideas enter and influence society, and vice versa. 'Designing' distinguishes many fields, and defines them as professions. Academically, this pervasiveness of design is manifested, at least in one form, as design science research.

Compared with the physical, life and social sciences, design science research is in its relative infancy. As a recognized scholarly field of endeavour, its existence may be characterized in mere decades. Scholarly venues for academic discourse and publication in design are vibrant, mature and impactful, yet relatively short lived. Academic positions in design science research at the world's most distinguished institutions of higher education have only recently solidified and gained significant traction. International societies and organizations have likewise only recently been created, and are emerging at an amazing rate. This relatively young and exciting existence of design science research begs the question: what is design science research today, and what might it be in the future?

Design science research represents the scientific study of design. It includes a number of driving characteristics.

- Systematic study, identification, and recognition of underlying principles (such as in Altshuller, G. (1997) *40 Principles: TRIZ keys to innovation*, L. Shulyak, & S. Rodman (Eds.). V.1, Technical Innovation Center, Inc., Worcester, MA).

- Guidelines for its execution and rigour, such as those espoused by Hevner et al. (Hevner, A.R., Ram, S., March, S.T. & Park, J. (2004) 'Design science in information systems research', *MIS Quarterly* 28, 75–105), design as an artefact (service or system), problem relevance, design evaluation, research contributions, research rigour, design as a search process, and research communication.

- Application of the scientific method and related design research methods (DRM), including inductive and deductive research methodologies (Blessing, L.T. & Chakrabarti, A. (2009) *op. cit.*).

- Study and advancement of design processes, theory, methods and practice.

- Collaborations of multiple disciplines and multidisciplinary approaches to the creation, validation and translation of science-based design knowledge.

- Partnership and interconnectedness with the humanities, arts and social sciences (HASS) given design as a human endeavour, or at least to impact human existence and society.

While these characteristics help to define design science research, and while significant advancements and impacts have been realized, design science research, today, is rather disciplinary centric and dispersed. Particular disciplines, such as engineering, architecture, information science, graphic arts and industrial design, perform design research in various forms and with particular venues for archival publications of research findings. Cross-disciplinary initiatives are reported and published, but at a much lower rate than within the disciplines. Even with the recognized findings of disciplinary design science research, the conceptual network of design science research is sparsely connected, recognized and cited between the disciplinary nodes. There are emerging linkages, but the network is nascent.

Development of this network for the future holds great promise. There exist multiple dimensions that will catalyse, enrich and cultivate this network, and design science as a research field, including the following.

- *Grand Challenges:* There is value and merit to the ideal study of design, its processes and principles. However, the scientific study of design should not be performed in isolation, but in the context of technological advancements, services, industrial processes and societal need. The pursuit of solutions to the world's grand challenges can provide no better forum for this context.

- *Design Research Thrusts:* Design research thrusts define the areas of design research that are critically important to advance design science and ultimately affect design practice. The full-value chain of design, from identification of an opportunity through implementation and sustainable operation, defines innumerable possibilities and thrusts that could be pursued. The continued development and evolution of these thrusts will greatly enable design science research.

- *Interactions*: The pursuit of design science research through the interaction of grand challenges and design research thrusts can have profound effects. If many multidisciplinary design science projects include at least one grand challenge (or rich and meaningful application or opportunity) and one design research thrust, interaction effects may lead to fascinating results as a feedforward and feedback system. As research or practice is carried out in grand challenges, the results will inform the need for improved design theories, principles, processes and methods. And as design research is carried out in design thrusts, the effect of designing solutions to grand challenges will be more pronounced.

- *Convergent Research:* Design science research represents the balancing of traditional disciplinary research and contemporary convergent research, i.e., achieving higher levels of integrative research across disciplines. Such research is expressed in different forms: multidisciplinary, interdisciplinary and trans-disciplinary. The design science research community has the opportunity and necessity to explore, prototype, test, study and practice the mechanisms of convergent research in new and exciting ways.

- *Big-D Design*: Design science research must take on a very broad view and understanding of design, denoted here as 'Big-D Design' (Magee, C.L., Leong, P.K., Jin, C., Luo, J. & and Frey, D.D. (2012) 'Beyond R&D: what design adds to a modern research university', *International Journal of Engineering Education*, 28, 397–406; Wood, K.L., Rajesh Elara, M., Kaijima, S., Dritsas, S., Frey, D., White, C.K., Crawford, R.H., Moreno, D. & Pey, K.-L. (2012) 'A symphony of designiettes – exploring the boundaries of design thinking in engineering education', *ASEE Annual Conference, San Antonio, TX*). 'Big-D Design' includes all technologically intensive design, from architectural design to product design, software design, service design and systems design. It is design through conception, development, prototyping, manufacturing, operation, maintenance, recycling, reuse and overall sustainability – the full value chain. It includes an understanding and integration of the liberal arts, humanities and social sciences. In short, Big-D encompasses the art and science of design.

- *Epistemology Relationships of Design*: Advancement of design science research will be needed in the epistemological relationship of design science to natural science, social sciences and engineering science. An aggressive attempt to clarify these relationships will have great value in setting an agenda for pursuing design science research.
- *Pinnacle of Design*: Pinnacle design opportunities have the characteristics of being cross-disciplinary, 'wicked' in nature, impactful on society (making a difference and making a splash), recognized and appreciated by one or more groups or communities, and requiring innovative solutions that have not existed previously. Design science research can benefit greatly through the pursuit of pinnacle design opportunities through the translation of design science knowledge to practice.
- *Pervasive Design Practice*: In the growing global interactions and flat world, responsiveness, flexibility, changing work force and sustainability are becoming more pronounced. These factors lead to a natural need for design capabilities, skills and mind set across all professions and organizations. Design science research will be affected by these factors and associated phenomena, and will need to be responsive to them. New knowledge, educational approaches and partnerships will not be created just for designers or selected disciplines, but for all people.

Design science research today is exciting and impactful. This excitement and impact will continue and increase, but design science research in the future will be profound and expand across grand challenges, between emerging design research thrusts, through convergent research, across the full value chain of design, throughout communities, organizations and cities, and across national and cultural boundaries. Design science research will continue to build a cumulative research enterprise around design and upon a reliable base. It will favourably impact design practice by the development of new methods, theories, guidelines, heuristics and principles that when applied directly lead to superior results for practicing designers, teams, communities and organizations. It will also favourably impact practice through results that point to superior education methods (Dym, C.L., Agogino, A.M., Eris, O., Frey, D.D. & Leifer, L.J. (2005) 'Engineering design thinking, teaching, and learning', *Journal of Engineering Education*, 94(1), 103–120) that can involve better basic knowledge structure to support design and better exposure to methods and experiences that are effective in practice, business and social enterprises.

Bernard Yannou

Design designates the result as well as the process of creating goods, services, and any man-made socio-technical system. Design must be addressed scientifically, as important stakes are concerned, such as economic competition, healthcare or conditions of sustainability of human activities. In essence, design consists of starting with issues, goals and expected performance and proposing acceptable and feasible design plans. Design is inherently linked to the combinatorial burden of solution scenarios, which must be *a priori* generated in a probabilistic manner to maximize the value creation likelihood and *a posteriori* confirm that the multi-attribute performance for the different stakeholders – clients, beneficiaries, decision makers – presents a good compromise in time and space.

Time means that a newly created design must be, as much as possible, durable in terms of lifetime, perennial for a company or sustainable for the environment. Lifecycle thinking has now become a fundamental principle for developing new designs and managing their life scenarios appropriately in contributing to a circular economy. Space means that a newly created design must be, as much as possible, universal, i.e., adapted to a diversity of people's needs, cultures and morphologies with no or few adaptations, and robust, i.e., not or little affected by purchasing, usage and recycling conditions for effectively delivering the expected performance. When a single design solution does not suffice to cover the diversity of expectations, a partitioning of expectations (several designs to fulfill expectations) or of customers (market segments and product variants) can be used with a common product or process platform permitting variants and customization. Operations management, cost modeling and customer preferences, decision-making and optimization are here necessary.

These time and space compromises require collection of increasing amounts of information about real lifecycle conditions and user behavior, preferences and satisfaction. The Internet of Things and other smart activities will completely change design activity. More and more products must be conceived as interacting artifacts, observing and influencing the behavior of users. Products must be considered as pools of services made of mobile apps, themselves embedded in company ecosystems of services. For instance, a sensor device for monitoring sleep quality contributes to a personal e-health diagnosis system in a company ecosystem. A new design will be more and more connected to different systems: other devices communicating with it during its use, cloud databases for big data analysis benefiting companies and users, and systems for security, diagnosis, monitoring or maintenance. System modeling and design are determining the knowledge areas to develop in the near future in order to control product interoperability, interfaces, adaptation and value contributions. Consequently, more and more, design will also concern business models, which are often today set aside (before and after) the core design process performed by design engineers and industrial designers. This is why business developers must integrate design teams for designing new product offers together. Likewise, lead users must be more involved in providing innovation insights, for concept appraisals and word-of-mouth advertising during product launch. Lastly, design science cannot ignore anymore the management parts of companies like strategic and technological roadmapping, front-end innovation strategies and projects, information management, innovation culture and processes. In conclusion, design must be a science made of a large number of disciplines.

What: John Gero's Synthesis

Designing is one of the most profound of human intellectual activities. It is the way in which humans intentionally change the world around them. Designing has been written about for at least 4,000 years, starting with the *Epic of Gilgamesh* (approximately 2,100 BC), where instructions for a producing a boat are given, and the *Code of Hammurabi* (approximately 1,750 BC), where the social implications of poor design and construction are detailed. Vitruvius' *De architectura* (around 50 BC) covered both machine and building design, and outlined design knowledge in the form of both prescriptive and performance rules. He also described evidence-based approaches related to the selection of materials. In 1452, Leon Battista Alberti published *De re aedificatoria: Ten Books of Architecture*, which introduced the notion of design process as an intellectual activity. These and other works prior to modern times attest to designing being an identifiable act in both the military and civil domains.

Designs are recognized as one of the most significant means for a society to improve its economic and social well-being: designs add economic, safety and social value to what already exists. Today, we inhabit a world that is increasingly designed and where the natural component of our world continues to decrease. Even areas such as human organs that were considered the preserve of nature are being increasingly designed. Given designing's importance in our lives it is surprising that designs and designing are so little understood compared with the physical sciences. Formal research into designing and designs commenced only after the Second World War in the English-speaking world. In the intervening 50 years, research into designing has developed increasingly along disciplinary lines. During this time, design research has adopted the scientific approach to the production of knowledge, primarily through the elicitation of evidence to support claims about designs and designing. Disciplinary-based design research has obscured commonalities in designing across disciplines and hidden applicable research results within individual disciplines.

The *Design Science* journal provides a platform for the publication, dissemination and archiving of research that is accessible across disciplines. Papers can be from a single discipline, multidisciplinary or interdisciplinary in the recognition that design is a discipline in its own right and that often commonalities cannot be seen because of the disciplinary focus of the publication location.

This editorial contains contributions from the various editors of the journal in response to the request to put down thoughts about future design research. A count of the concepts mentioned in these contributions gives an idea of their focus. The most common concept mentioned, as expected, is design science: what it is and what its goals and roles are. This is followed by interdisciplinarity, indicating the importance of an increasingly observed phenomenon that designing is not restricted to a single discipline. The next two most common concepts mentioned are products and processes. These are well-developed research areas but remain significant research topics even as we continue to increase our knowledge about them. The next two most common concepts mentioned are understanding humans and including humans in designing. Understanding humans covers individuals and teams designing from cognitive and brain science perspectives as well as including them in systems engineering. Including humans in the ambit of designing covers user responses to products and crowd behavior. This is a consequence of our recent ability to capture more and more data about people and their interactions with designs while making decisions about them. The next two are creativity and knowledge, with models, theories, systems practice, big data and change all following.

What these contributions indicate is that designs and designing are rich in researchers' conception of them as well as being rich in what needs to be researched. This implies a lack of a complete understanding of both the depth and range of designing.

A thread that runs through these contributions is the notion that researchers and then practitioners can all benefit from a deeper understanding of designing and designs irrespective of the disciplinary source of the research that supports that understanding.

How

How then is *Design Science* different from other journals?

Making research results accessible across disciplines requires effort by both authors and readers. *Design Science* articles will likely have longer introductions and literature reviews and more explanation of terms than is typical for discipline-specific journals. Authors and reviewers in disciplinary journals usually discard such material as unnecessary 'padding.' Papers become more efficient at the expense of wider accessibility. For *Design Science*, I would expect the typical reader to follow at least 40% of any typical article and, having no expertise in the particular topic, to be drawn into further study of additional work from the references to fully comprehend what is put forth. Perhaps a fair aspiration for some *Design Science* articles is that they would be the first reads for researchers getting into a field or topic new to them.

Crossing disciplinary boundaries in an article does *not* mean that all articles must be interdisciplinary. Single-discipline papers are fine, they just need to be as *accessible* as possible to other disciplines.

The open-access wave is clearly the way of the future. This shifts the costs of publication from the readers to the authors and their home institutions. The business models are evolving and will reflect the developing attitudes of the scientific community and research sponsors. The publisher and the Design Society have agreed on a fee structure that may seem steep, but it is reasonable compared with situations in other scientific areas. The fee is significantly reduced for Design Society members. Moreover, authors of accepted papers can ask the Editor for a fee waiver for cause. Such cause may be that the work is not sponsored externally, the sponsor or the home institution does not support open access or the authors come from developing countries with few resources available to support research. If authors who can pay the fee do pay it, this system should work reasonably for all parties.

The publisher, Cambridge University Press, is a non-profit organization, like the Design Society. While publication requires good business sense, I find that dealing with non-profit organizations mitigates the occasional sense of exploitation within our community, particularly in its younger members.

The journal publishes primarily research papers; it also publishes reviews and survey papers with strong tutorial elements, shorter notes (for example, pertaining to a particularly interesting exemplification of design science in a design artifact or practice), editorials, and book, software and design tool reviews. The journal also accepts position papers. These are hard to write but valuable when done well with well-structured and supported arguments.

Some important practicalities for running the journal are as follows. Manuscripts are submitted in simple PDF. John Gero or I undertake their review.

We then assign an Associate Editor the task of conducting the review, collecting typically three anonymous reviews, and making a recommendation. Final decisions rest with the Chief Editors. The review time is targeted to be eight weeks for the first round of reviews. The remaining time for final decision depends on revision needs.

The articles are published immediately online upon acceptance and completion of production. There are no issues during the year, only annual volumes. This expedites publication. ISI indexing is important for many authors. Indexing will commence as soon as a sufficient number of papers is published. Once indexing starts, it will include all papers published from the journal's inception.

Welcome to the *Design Science* journal, and please join our community!